Net-Zero Emissions Transition in Chemical and Process Industries

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Net-zero activities are addressing the climate and resource problems. Energy and resource efficiency, and simple circular economy are addressing the welcomed low hanging fruits. The European Commission has proposed the Net-Zero Industry Act (NZIA) to promote the production of clean technologies in the EU and prepare for the transition to clean energy. It shall significantly contribute to decarbonization by developing batteries, biogas/biomethane, carbon capture, and sustainable and alternative fuel technologies. Achieving net-zero emissions in the chemical process industries necessitates a holistic approach that combines technological advancements, supplies chain considerations, and societal transformation. While challenges exist, the CPI sector has the potential to significantly contribute to global emission reduction efforts. Collaboration, innovation, and a transition towards sustainable lifestyles are crucial for turning net-zero emissions into a tangible reality.

net zero | energy | process industries | emissions | climate | chemicals | biomass | waste | cement | metals

1. Introduction

The chemical industry holds a pivotal position in the global economy, generating numerous jobs and making significant contributions to the GDP. By prioritizing emissions reduction, this industry can achieve substantial growth, which is projected to reach 2.5 times current levels by 2050. It also has the potential to play a crucial role in facilitating the transition to net-zero emissions across other sectors. Aligning with the Paris Climate Agreement, the chemical industry can effectively manage its own greenhouse gas emissions (Scope 1–3) while pursuing remarkable growth [1]. To realize these advantages, the European Commission has outlined a transition pathway specifically tailored to the chemical industry [2].

Having established the significance of research and the growing awareness of net-zero emissions in the chemical and process industries, scholars now turn to innovative approaches and transformative actions. These integrate principles of the circular economy and climate action, essential for a sustainable and low-carbon future [1]. Urgently limiting anthropogenic CO_2 release to levels absorbable by natural sinks becomes imperative [3]. Critical processes such as hydrogen production, ammonia synthesis, CO_2 reduction, and novel aspects of acetylene chemistry are vital for creating a sustainable chemical sector [4]. Innovative approaches play a crucial role in waste reduction and the discovery of new utilization methods [5].

In addition to developing innovative technologies, the chemical industry needs a comprehensive and coordinated strategy that incorporates its interconnected supply chains to effectively achieve the goal of net-zero GHG emissions [6]. Even what was considered innovation some time ago must keep pace with a new paradigm. For example, conducting a thorough life cycle assessment (LCA) prior to establishing a biorefinery and its entire supply chain is essential to comprehensively assess environmental impacts [7]. Recently, circular design strategies, including the design-for-disassembly (DfD), have been promoted to address waste production, raw material consumption, and lack of reuse; however, their environmental impacts are not always measured [8]. Digital transformation is also important for decarbonization. Several computer-based tools facilitate design and allow more rapid assessment of the environmental impacts of chemical processes [9], as traditional LCA can take weeks to complete. One prominent avenue is the use of artificial intelligence (AI) as a valuable tool for mitigating CO_2 emissions in the chemical industry [10]. It is possible to integrate AI data and methods to estimate sustainability metrics and design for more sustainable chemical processes [11].

System engineering approaches are relevant to the chemical and process industries, as well as to individual sectors with specific characteristics. The production of cement is a significant contributor to global CO_2 emissions, accounting for more than 7% of the total which can be reduced in many ways. Firstly, carbon emissions in Ordinary Portland Cement (OPC) can be brought down with the use of alkali-activated materials (AAM), which are traditional binders [12]. Secondly, the proposed option for reducing CO_2 emissions in the cement industry is the use of CO_2-containing flue gas and cement kiln dust (CKD) for producing mineral carbonates that serve as non-reactive fillers for blending cement [13]. Thirdly, the use of alternative supplementary cementitious material (SCM), such as biochar, obtained by pyrolyzing rice husks at a temperature of 550 °C, can be performed [14].

In addition to concrete production, the manufacturing of zeolites calls for more sustainable production due to a high energy consumption and substantial CO_2 footprint [15]. Similarly, achieving the production of high-quality iron at low temperatures is preferred [16].

Steel production is responsible for another 7% of CO_2 emissions globally and for 5% of emissions in the EU, which is why the EU steel industry is moving forward with hydrogen-based steelmaking as a decarbonization strategy [17].

In the effort to achieve net-zero greenhouse gas emissions, the use of CO_2 as a feedstock plays an important role [18][19]. Carbon capture and storage (CCS route, [20]) can be conducted with various mechanisms such as pre-combustion, post-combustion, oxy-fuel technologies, direct air capture, chemical looping combustion and gasification, ionic liquids, biological CO_2 fixation, and geological CO_2 capture [21].

The sequestration and reduction of CO_2 require the development of a portfolio of technologies [22]. In addition, the integration of various renewable energy sources with CO_2 capture processes [23] and carbon-neutral processes to replace current industrial processes is urgently needed. Studies have been conducted on the sustainable synthesis of ammonia and iron with high value nanocarbon products by electrolysis in molten salt(s) with the introduction of the Solar Thermal Electrochemical Process (STEP) [22]. There is also potential for closing the carbon cycle (C-3) for the nation's carbon-intensive industries, such as the production of olefins by reducing lignite for power generation in Germany and the need to increase carbonaceous waste recycling [24].

There is a critical need to further develop cost-effective technologies related to the use of CO_2 as a feedstock, valuable chemical, and material for fuels [22]. A carbon-neutral fuel is characterized by the utilization of the atmosphere as the primary source of hydrocarbons, followed by combustion that releases CO_2 as a byproduct [25]. In the area of thermo-catalytic CO_2 conversions to clean fuels, the core-shell catalysts for thermo-catalytic CO_2 conversion to syngas and fuels have recently received much attention [26].

2. Net-Zero Emissions Transition in Chemical and Process Industries

2.1. Sustainable Development Goals

The 17 SDGs with 169 targets are the main action plan of the Paris Agreement [27]. The chemical and process industries play an essential role in achieving the SDGs by addressing environmental, social, and economic challenges and making an important contribution to the global economy by providing critical products and services to various industries. The pursuit of the SDGs is consistent with promoting clean production methods, optimizing resource efficiency, and minimizing environmental impact. Industry efforts to reduce GHG emissions and adopt CCUS techniques are an essential part of global climate action. In addition to environmental aspects, the chemical and process industries also impact the social and economic dimensions of sustainable development.

The World Business Council for Sustainable Development (WBCSD) has coordinated an SDG roadmap for the chemical sector proposed by leading chemical companies and industry associations [28]. Ten goals were identified as a priority of the sector: 2—Zero hunger, 3—Good health and well-being, 6—Clean water and sanitation, 7—Affordable and clean energy, 8—Decent work and economic growth, 9—Industry, innovation, and infrastructure, 11—Sustainable cities and communities, 12—Responsible consumption and production, 13—Climate action, and 14—Life below water. The roadmap outlines 18 impact opportunities that can contribute to the 10 priority SDGs. They are grouped into five key themes: food, water, people and health, energy, infrastructure, and cities. To reach the goals by 2030, innovation will be needed across products and processes, in cooperation with partners.

The International Council of Chemical Associations (ICCA) published six themes cross-referenced to specific SDG indicators: health and well-being; sustainable consumption and production; energy, environment, and sustainable cities; sustainable economies; learning and education; and public-private partnerships [29]. The article presented some other links to several trade associations, and examples of several chemical companies' approaches.

American Chemical Society (ACS) has identified seven priority SDGs and five additional SDGs that are foundational to the work of the chemistry community [30]. The ACS Green Chemistry Institute organized various principles of green chemistry and engineering and presented them in three groups: (1) maximize resource efficiency; (2) eliminate and minimize hazards and pollution; (3) design systems holistically and using life cycle thinking—requiring chemists and chemical engineers to design, measure, be efficient, and be sustainable [31]. The European Chemical Industry Council (CEFIC) published a report focusing on four areas of impact: the low-carbon economy, resource efficiency, the circular economy, and for people and the planet [32].

2.2. European Green Deal

EGD plans to transform the EU into a modern, resource-efficient, and competitive economy, ensuring: (1) no net emissions of greenhouse gases by 2050 (at least 55% reduction by 2030), (2) economic growth decoupled from resource use, and (3) no person and no place left behind [33]. The European Green Deal shall improve the well-being and health of citizens and future generations by providing: (1) fresh air, clean water, healthy soil, and biodiversity; (2) renovated, energy-efficient buildings; (3) healthy and affordable food; (4) more public transport; (5) cleaner energy and cutting-edge clean technological innovation; (6) longer lasting products that can be repaired, recycled, and re-used; (7) future-proof jobs and skills training for the transition; (8) a globally competitive and resilient industry. In 2023, the Commission presented an EGD Industrial Plan to enhance the competitiveness of Europe's net-zero industry and support the fast transition to climate neutrality [34]. It is based on four pillars: (1) a predictable and simplified regulatory environment, (2) speeding up the access to finance, (3) enhancing skills, and (4) open trade for resilient supply chains.

CEFIC sees the transformation to a climate-neutral and circular economy as a key driver of European jobs and economic growth [35]. The European chemical industry has the ambition to become climate neutral by 2050. To reach it, decarbonized and circular economy solutions shall be developed by the chemical industry. Access to abundant and competitive low-carbon energy, development of relevant infrastructure, as well as new market opportunities related to sustainable products, are key conditions to ensure that the industry stays globally competitive during the transition [36]. Costs and opportunities of the EGD for the chemical industry for core equipment and the design, construction and modification of facilities have been estimated to be 400–600 GEUR by Accenture [37]. Chemicals for the EGD are foreseen to be used in (1) Renewable energy, (2) Clean Road transport, (3) Circular economy, (4) Public health, (5) Electronics, (6) Aerospace, etc.. The chemical industry is indispensable to Europe's strong and sustainable economy of the future, as chemicals are present in almost every strategic value chain [38].

The EU is the world's biggest glass producer, with a market share of around one-third of the total world production. Glass production in the EU reached 36.8 Mt in 2020 according to Glass Alliance Europe. It comprises five subsectors: 60.4%—Container glass, 29.2%—Flat glass, 3.2%—Domestic glass, 5.3%—Fibers (reinforcement and insulation), and 2.1%—Special glass [39].

2.3. The Role of Chemical Process Systems' Engineering

The vision for the chemical industry to achieve net-zero emissions by 2050 exists. The Center for Global Commons at the Tokyo University & Systemiq, for example, identified three main strategies: replacing fossil fuels with alternative feedstocks, switching from fossil to renewable energy sources, carbon capture, storage, and utilization

[1]. It highlights the main chemicals, namely green hydrogen, ammonia, methanol, olefins, and aromatics, whose synthesis needs to be switched from fossil to non-fossil feedstocks, specifically hydrogen from the electrolysis of water, nitrogen from the air, and carbon from biomass, waste, and/or captured CO_2. Also listed are seven major production processes for the carbon-free production of primary chemicals: (i) electrolysis of water to produce green hydrogen, (ii) reforming of methane, (iii) gasification of biomass and waste to produce syngas followed by methanol and ethanol synthesis, (iv) CO_2 capture and conversion to methanol with green hydrogen, (v) steam cracking of biomass and waste to produce olefins and aromatics, (vi) catalyzed conversion of methanol to downstream chemicals (methanol to X), and (vii) dehydration of ethanol to olefins.

Increasing efficiency. To reduce resource consumption, the efficiency of bio-based chemical processes must be increased. The conversion of renewable and alternative resources, e.g., biomass and waste, is often less efficient economically and technologically than the conversion of fossil resources [40]. There is a need to encourage investment in low-carbon technologies and carbon capture and storage/utilization through various financial incentives [41]. On the other hand, fossil-based technologies are still economically attractive in many cases and should be charged accordingly for CO_2 emissions. A higher CO_2 tax in process optimization promotes higher reactant conversion, lowers feedstock consumption, and increases the required investment by encouraging the use of more efficient process units and higher quality feedstocks [42].

Multi-Objective Process Optimization. The introduction of technologies to move the chemical industry closer to net-zero production involves many conflicting criteria. Reductions in greenhouse gas emissions are usually associated with reductions in economic benefits [43]. It was shown by Kasaš et al. that trade-off solutions between economic, operational, and environmental criteria can be achieved if an appropriate objective function is used [44].

Process Integration. Process integration is one of the main methodological approaches that contributes significantly to the decarbonization of the chemical industry [45]. It leads to a lower consumption of heat, energy, and materials, and thus lower emissions [46]. The use of process integration is expanding to include greenhouse gas emissions' planning and reduction [47]. It is a mature approach that includes various methods such as pinch analysis, mathematical programming, and P-graphs [48]. The most common applications are the integration of hot and cold streams within the process and in total sites which offer the possibility of using the excess process heat in residential areas [49].

2.4. Process Industries

The chemical sector is the largest industrial energy consumer and the third largest industry subsector in terms of direct CO_2 emissions [50]. This is largely because around half of the chemical subsector's energy input is consumed as feedstock—fuel used as a raw material input rather than a source of energy. In 2021, direct CO_2 emissions from primary chemical production reached a total of 925 Mt [51]. In the Net-Zero Emissions by 2050 Scenario, CO_2 emissions will be reduced by 17% until 2030—both the private and public sectors will need to achieve technological innovation, efficiency gains and higher recycling rates. Ammonia production is responsible for the highest fraction of emissions, followed by high-value chemicals (i.e., ethylene, propylene, benzene, toluene, and mixed xylenes) and methanol.

2.4.1. Chemical Industry

Direct CO_2 emissions from primary chemical production reached 925 Mt in 2021 [51]. This represents a 5% increase from the previous year, due to higher production levels than in 2019 [52]. However, the CO_2 intensity of primary chemicals has remained relatively stable at around 1.3, indicating the mass ratio of emitted CO_2 to primary chemicals produced. On a global level, the chemical industry is responsible for about 4% of global greenhouse gas emissions.

On a more positive note, the chemical industry in the EU has made remarkable progress in reducing its environmental impact. Despite an increase in the production of more than 43% since 1990, greenhouse gas emissions from chemical production in the EU-27 have decreased by 55% compared to 1990 [53].

Industrial chemicals, such as ammonia, methanol, and ethylene, are crucial feedstocks for over a dozen different sectors—from healthcare, agriculture, and construction, to packaging, cars, and textiles [54]. However, the chemical industry is also deeply involved in many issues related to Planetary Boundaries, such as greenhouse gas emissions, the discharge of waste plastics into the oceans, deviations from the natural cycle of nitrogen and phosphorus, and the loss of biodiversity [1].

The chemical industry plays a significant role in global emissions due to its energy-intensive processes and reliance on fossil fuels. However, several promising and state-of-the-art technological innovations are emerging to shift the industry towards net-zero emissions.

Carbon Capture, Utilization, and Storage (CCUS) [55][56]. CCUSs capture CO_2 emissions from industrial processes and either store CO_2 underground by injecting it into suitable geological formations or utilize it for other purposes [57]. Technologies such as electrochemical conversion [58][59], catalytic hydrogenation [60], and photocatalytic conversion of CO_2 [61] have the potential to reintegrate captured CO_2 into the value chain by converting it into fuels and chemicals.

Electrification and renewable energy integration. Shifting from fossil fuel-based energy sources to renewable energy is crucial for decarbonizing the chemical industry. The electrification of processes [62][63], by switching from fossil-powered processes to electricity-powered processes (e.g., electrical furnaces and boilers, heat pumps) and the integration of renewable energy sources [64][65][66][67], such as solar, wind and biomass, can reduce or eliminate the need for fossil fuel combustion.

Hydrogen as a feedstock and energy carrier. Hydrogen produced from renewable sources (green hydrogen) can serve as a clean feedstock and energy carrier in chemical manufacturing processes. It can be produced by biological processes [68][69], e.g., direct, and indirect photolysis, photo-fermentation, or dark fermentation), by thermochemical processes [70], e.g., biomass pyrolysis and gasification, or electrolysis of water [71], by electrolysis, e.g., proton exchange membrane electrolysis, anion exchange membrane electrolysis [72], or solid oxide electrolysis [73].

Bio-based feedstocks. The utilization of bio-based feedstocks derived from biomass can help reduce the industry's reliance on fossil fuels. Biomass, such as agricultural residues [74], and food wastes [75], can be converted into bio-based chemicals through various processes such as fermentation [76], enzymatic conversion [77], or thermochemical conversion [78].

Process optimization and advanced catalysts. Improving the efficiency of chemical processes and developing advanced catalysts [79][80], can reduce energy consumption and emissions through increased conversion and selectivity and milder operating conditions with respect to temperature and pressure.

Circular economy and recycling. Embracing a circular economy approach within the chemical industry involves designing products for reusability, recycling, or biodegradability [81]. Developing innovative recycling technologies, such as chemical recycling, enables the recovery of valuable materials and reduces the need for virgin feedstocks [82].

Artificial intelligence (AI) and data analytics. AI and data analytics can be employed to optimize processes [83], predict and detect anomalies [84], etc. AI and data analytics will play a major role in boosting new product development, increasing the safety and reliability of chemical production processes, and enhancing the sustainability of chemical supply networks.

2.4.2. Pharmaceutical Industry

The pharmaceutical industry plays a vital role in advancing human health, but its environmental impact cannot be overlooked. The manufacturing processes involved in pharmaceutical production generate significant GHG emissions [85], contributing to climate change. The pharmaceutical industry is responsible for an estimated annual direct emission of approximately 52 Mt of CO_2 equivalent worldwide [86]. It is important to note that this estimation solely accounts for emissions directly generated by pharmaceutical activities, without taking into consideration the indirect emissions associated with energy use throughout the entire supply chain. Indirect emissions may arise from various sources such as the transportation of medicines, lighting and refrigeration in distribution facilities, and other energy-related processes.

The pharmaceutical industry is exploring various state-of-the-art technological innovations that hold promise for shifting towards net-zero emissions. Several key advancements have emerged in recent years:

Green Chemistry and Sustainable Synthesis. The adoption of green chemistry principles and sustainable synthesis methods is gaining traction in pharmaceutical manufacturing. This approach focuses on minimizing the use of hazardous materials [87], optimizing chemical processes, and designing more environmentally friendly reactions to reduce waste generation and energy consumption [88][89].

Process Intensification and Continuous Manufacturing. Process intensification involves optimizing manufacturing processes to improve efficiency, reduce resource consumption, and decrease emissions. Continuous manufacturing, as opposed to batch processing, allows for streamlined operations, reduced waste, and improved energy and material efficiency, thereby lowering the overall carbon footprint [90][91][92][93].

Decentralized Energy Generation and Advanced Energy Management Systems. Utilizing waste-to-energy systems [94], solar photovoltaic systems, wind turbines, and biomass energy facilities on-site can significantly reduce reliance on fossil fuels. Advanced energy management systems integrate energy storage, demand response, and smart grid technologies. This enables the optimization of energy use, real-time monitoring of energy consumption, and identification of opportunities to improve energy efficiency.

Circular Economy and Waste Reduction. Implementing circular economy practices within the pharmaceutical industry can minimize waste generation and resource depletion [95][96]. Recycling and repurposing of materials [97], implementing closed-loop systems [98], and developing innovative recycling technologies [99] enable the recovery of valuable resources, reducing the reliance on virgin materials and reducing emissions associated with raw material extraction and production.

Digitalization and Data Analytics. Leveraging digital technologies, such as artificial intelligence (AI), machine learning, and data analytics [100][101], can identify novel and sustainable reaction pathways and thus directly or indirectly optimize processes, improve energy efficiency, and identify opportunities for emission reduction. Advanced modeling and simulation tools [102] can also aid in designing more sustainable and environmentally friendly pharmaceutical manufacturing processes [103][104].

2.4.3. Cement Industry

Around 40% of CO_2 emissions from fuel combustion worldwide and 25% of global GHG emissions are attributed to the built environment [105]. Among these figures, cement production stands out as one of the most significant contributors, responsible for 6–10% of global CO_2 emissions [106].

The cement and concrete industry can utilize the following strategies to accomplish their decarbonization objectives.

Reducing the fraction of clinker in cement. The emission from cement production is predominantly caused by clinker, accounting for roughly 90% of the total [107]. This makes it imperative for industry stakeholders to prioritize finding solutions for clinker-related emissions. To decarbonize the industry, cement manufacturers can explore the possibility of replacing clinker with alternative materials such as fly ash [108][109], granulated blast furnace slag [110], calcined clays [111] and even red mud, to some extent [112][113].

Reducing energy-related CO_2 emissions. To decrease emissions associated with energy usage, industry participants are actively investigating alternative fuels (biomass and municipal and industrial wastes and their mixtures) [114][115], developing innovative technologies such as kiln electrification [116][117], oxy-combustion [118], and heat generation via plasma technology [119].

Carbon capture, storage, and utilization. The CO_2 emissions captured from production processes [120][121] can be reintegrated into the value chain through various means [122]. For instance, they can be utilized in the production of recycled clinker (mineralization, [123]) or incorporated into fresh concrete (carbon curing, [124]). Moreover, concrete structures can absorb a substantial amount of CO_2 during their lifespan through a process called recarbonation.

4.4.4. Glass Industry

The UK glass industry has increased energy efficiency by 50% in the last 40 years by using waste heat, Organic Rankine Cycle, or steam turbine to preheat raw materials, fuel, or oxidants [125]. Oxyfuel combustion is using oxygen instead of combustion air, yielding energy savings of 10–15% and reduced emissions. Fossil fuels can be replaced by biofuels with reduced emissions of NOx. All electric furnaces are an established technology in the glass sector and are more efficient than gas-fired furnaces. The latest development is using up to 80% electricity with 20% gas energy (hybrid furnaces) with the future opportunity to consider hydrogen combustion using 100% hydrogen as well as different proportions of hydrogen blended with natural gas for glass melting.

Process emissions can be reduced by using a higher fraction of recycled glass which substitutes the carbonate raw material and reduces CO_2 emissions [125]. Alternative raw materials, such as calcium oxide, mineral slags, waste incineration ashes, etc., can replace carbonate raw material or reduce the melting temperature of the glass and thereby energy requirements. CCUS may be needed as a final stage for decarbonization.

2.5. Biotechnology

Industrial biotechnology, based on renewable resources, can save energy and significantly reduce CO_2 emissions. Bio-based chemicals can replace their fossil-based counterparts with significant GHG emissions reductions [126]. Bio-based plastics are potentially attractive in terms of specific emissions and energy savings. Governmental intervention can play a significant role in the effort to advance the industrial biotechnology sector toward lower GHG emissions, e.g., emissions trading systems (ETS) or tax for transportation emissions, pollution costs charged to petrol-based materials, labeling systems for bio-based materials and biofuels, public procurement supporting bio-based materials and sustainably produced biofuels [127].

2.6. Metals Production

2.6.1. Iron and Steel

CO_2 emissions and energy use in European steel production have already been halved since 1960 [17]. Presently, the EU steel industry is mainly focusing on hydrogen-based steelmaking as a decarbonization strategy. Carbon capture and utilization technologies will be developed in partnership with the chemical industry. Recycled iron and steel waste, and the electrolytic reduction of iron ore will be used for iron and steel production. Renewable electricity and transmission networks, hydrogen-related infrastructure or CO_2 transport, and storage infrastructures will be built.

2.6.2. Aluminum

An aluminum net-zero transition strategy will require [128]:

- Power decarbonization is critical: all smelters will need to switch to low carbon power by 2035, equating to approx. 1000 TW h of low-carbon electricity demand.
- Power decarbonization is necessary but not sufficient to decarbonize the sector; new technology for low carbon anodes and new refining technologies need to be commercialized by 2030.
- Recycled aluminum plays a critical role, expanding from 33% of supply in 2020 to over 50% by 2050.
- Mobilizing approximately 1 TUSD (10^{12} USD) of the investment over the next 30 years will be needed to deliver the transition for the primary aluminum sector, with over 70% of the sum required for supporting infrastructure, most of it for power supply.

2.7. Pulp and Paper

- The pulp and paper industry is among the top five most energy-intensive industries globally and is the fourth largest industrial energy user. This industry accounts for approximately 6% of global industrial energy use and 2% of direct industrial CO_2 emissions [129]. As the paper production will increase, greater efforts must be made to reduce the emissions intensity of production by 2030 by substituting fossil fuels with renewable energy sources, e.g., biofuels, accelerating the energy efficiency improvements, and reducing the energy needed for drying [130].
- Substituting more pulp by recycled wastepaper to over 60% by 2030.
- Installation of high-temperature heat pumps using waste heat sources inside the production process.
- On-site waste heat recovery and co-generation.
- Emerging technologies, e.g., heat recovery from thermomechanical pulping, black liqueur gasification, microwave drying, supercritical CO_2 or deep eutectic solvent.

EU believes that by 2050 the European pulp and paper industry can reduce its energy consumption by 14% and greenhouse gas (GHG) emissions by 62% compared to 2015 levels [131]. Carbon capture and storage (CCS) could further reduce GHG emissions. Biorefinery products from the pulp and paper mills could replace fossil fuels for light duty vehicles, be used as raw materials in the chemical industry, or as fertilizers.

2.8. Key Technologies Related to Net-Zero Emission

Several technologies, directions, and approaches have been identified as important for the transition to a net-zero economy. Some of these are tailored to a specific industry, such as the reduction of the fraction of clinker in cement in the cement industry, while others are across industries, such as carbon capture, electrification, waste reduction, etc. To indirectly assess the activity of the development and interest in respective fields as they pertain to net-zero emissions, a Google search was performed relating some of these to net-zero emissions.

3. Conclusions

In conclusion, recognizing the complex interlinkages between sectors and understanding that emissions need to be addressed holistically across the value chain are crucial aspects to successfully achieving this ambitious goal. Furthermore, the roadmap toward net-zero emissions must encompass not only net-zero energy production, but also net-zero feedstock production.

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